

## CHANDRA OBSERVATIONS OF THE EASTERN LIMB OF THE VELA SUPERNOVA REMNANT

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**Abstract.** We present results from two *Chandra*/ACIS observations of the so-called Vela “Bullet D” region on the eastern limb of the Vela supernova remnant. The Bullet D region is a bright X-ray feature, identified by Aschenbach et al. (1995) from the ROSAT All-Sky Survey, which protrudes beyond the blast wave on the eastern side of the remnant. It has been suggested that this feature is a fragment of supernova ejecta which is just now pushing beyond the position of the main blast wave. An alternate explanation is that the feature is a “break-out” of the shock in which inhomogeneities in the ambient medium cause the shock to be non-spherical. The *Chandra* image shows a fragmented, filamentary morphology within this region. The *Chandra* spectra show strong emission lines of O, Ne, and Mg. Equilibrium ionization models indicate that the O and Ne abundances are significantly enhanced compared to solar values. However, non-equilibrium ionization models can fit the data with solar O abundances and Ne abundances enhanced by only a factor of two. The *Chandra* data are more consistent with the shock breakout hypothesis, although they cannot exclude the fragment of ejecta hypothesis.

### 1. Introduction

The Vela supernova remnant (SNR) is a large (diameter  $\sim 8$  degrees), nearby supernova remnant associated with the Vela pulsar and is one of the brightest objects in the X-ray sky. Recent work indicates the distance to Vela is only  $250 \pm 30$  pc (Cha *et al.* 1999 and Jenkins & Wallerstein 1995), making it an ideal candidate for resolving fine structure in X-rays with the *Chandra X-ray Observatory*. ROSAT All-sky Survey observations showed a complicated morphology and revealed the outer extent of the remnant for the first time. Aschenbach *et al.* (1995) identified several features protruding beyond what is believed to be the primary blastwave as “explosion fragments”. The brightest of these

features is the so-called “Bullet D”. Tsunemi *et al.* 1999 and Miyata *et al.* 2001 observed “Bullet A” with *ASCA* and *Chandra* respectively and detected strong Si emission lines which they concluded was evidence that Bullet A was indeed composed of ejecta from the original explosion. Moriguchi *et al.* (2001) suggested that the bullet features were more likely the result of the interaction of the SNR shock with an inhomogeneous medium as indicated by the numerous molecular clouds identified by a CO survey of the region. Redman *et al.* (2000) noted the coincidence of the bright optical filamentary nebula RCW 37 and Bullet D. We proposed two *Chandra* observations, one at the head of the bullet and the other in the “wake” in order to examine the proposed explanations for Bullet D.

## 2. Observations

*Chandra* observed the eastern limb of Vela in September 2000 with the ACIS-I detector. The exposure at the head of the Bullet D was 31 ks and the exposure in the wake region was 52 ks. Figure 1 displays the image from the head of Bullet D after selecting events in the 0.4 to 2.5 keV range, binning the data in  $2 \times 2''$  pixels, and smoothing the data with a Gaussian filter with a FWHM of  $3''$ . The data show a fragmented, filamentary structure consistent with a shock interacting with an inhomogeneous medium. If this feature were a fragment of ejecta from the explosion, one would expect a larger contrast in intensity of the X-ray emission from the head of the feature to the trailing edges as seen in Bullet A.

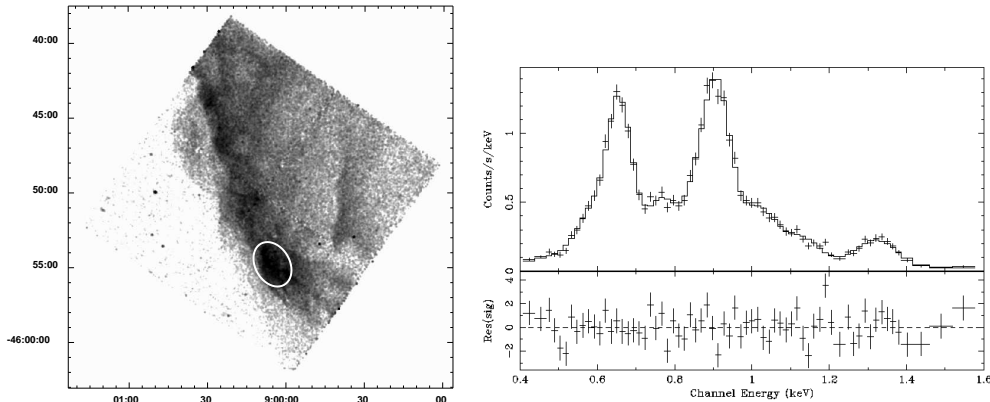


Figure 1. (LEFT) *Chandra* ACIS-I observation of the Eastern Limb of Vela. The data have been filtered to include energies between 0.4 and 2.5 keV and binned into  $2 \times 2''$  pixels. The data have been smoothed with a Gaussian filter with a FWHM of  $3''$ . The ellipse indicates the spectral extraction region. Figure 2: (RIGHT) Spectrum extracted from the ellipse in Figure 1 after applying the CTI correction.

## 3. Spectral Analysis

The frontside-illuminated (FI) CCDs on ACIS suffered radiation damage early in the mission which resulted in a large increase in the charge transfer-inefficiency (CTI) and a significant reduction in the spectral resolution. The observations

of the Bullet D are seriously impaired by this damage since the object covers all four CCDs on the ACIS-I array. We have used the CTI-correction software and appropriate response matrices developed at Penn State (see Townsley *et al.* 2000, Townsley *et al.* 2000a, and Townsley *et al.* 2000b). The CTI correction dramatically improves the quality of the data as demonstrated in our analysis of the spectra of the SMC SNR 1E0102.2-7219 (see Plucinsky *et al.* 2001). Fortunately, the spectrum of the Bullet D is quite similar to that of 1E0102.2-7219 in that both have strong lines of O, Ne, and Mg with little or no Fe.

We focus on the spectrum of the brightest part of the Bullet D feature described by the ellipse in Figure 1. The ACIS spectrum of this feature is shown in Figure 2. The dominant features are the OVIII Ly  $\alpha$  line at 654 eV, the NeIX triplet at  $\sim 910$  eV, and the MgXI triplet at  $\sim 1.34$  keV. We fit these data with a collisional ionization equilibrium (CIE) model and derived a best-fit temperature of  $\sim 0.45$  keV after fixing the  $N_H$  to be  $3.0 \times 10^{20} \text{ cm}^{-2}$  (see Dubner *et al.* 1998). At this temperature, the CIE model indicates that the O and Ne abundances must be enhanced by several times over solar values.

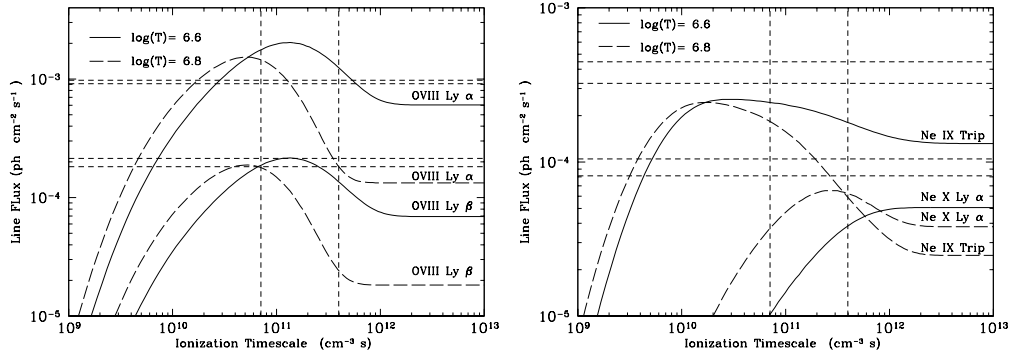


Figure 3. (LEFT) The predicted and measured emissivities of the OVIII Ly  $\alpha$  and Ly  $\beta$  lines as a function of ionization timescale and temperature. The measured emissivities are indicated by the dashed horizontal lines and the region of ionization timescales discussed in the text are indicated by the vertical dashed lines. Figure 4: (RIGHT) Same as Figure 3 except for the the NeIX triplet and NeX Ly  $\alpha$  line.

Next we fit the data with a model of a simple continuum plus Gaussians to represent the line emission. We used the ratios of OVII triplet/OVIII Ly  $\alpha$  and NeIX triplet/NeX Ly  $\alpha$  as non-equilibrium diagnostics. Both diagnostics indicated that temperatures below  $\log(T)=6.4$  are not consistent with the data. Both the O and Ne line ratios are consistent with ionization timescales in the range  $7.0 \times 10^{10} < n_e t < 7.0 \times 10^{11} \text{ cm}^{-3} \text{ s}$ . We can impose an upper limit on the ionization timescale of  $n_e t = 4.0 \times 10^{11} \text{ cm}^{-3} \text{ s}$  by assuming an age of 12,000 yr and a maximum ambient density of  $n_o = 1.0 \text{ cm}^{-3}$ . We can then compare the emissivities of the OVIII Ly  $\alpha$ , OVIII Ly  $\beta$ , NeIX triplet, and NeX Ly  $\alpha$  lines to the expected values. The measured emissivities are plotted against the expected emissivities as a function of temperature and ionization timescale in Figures 3 and 4. The measured Ne emissivity is higher than the predicted emissivity for all values of the ionization timescale regardless of temperature, indicating

that the abundance of Ne must be higher than solar. In the preferred range of ionization timescales from  $7.0 \times 10^{10} < n_{et} < 4.0 \times 10^{11} \text{ cm}^{-3}\text{s}$ , the Ne abundance required to be consistent with the model predictions varies from 1.6 to  $6.4 \times$  solar. The situation with O is significantly different. In the range of preferred ionization timescales from  $7.0 \times 10^{10} < n_{et} < 4.0 \times 10^{11} \text{ cm}^{-3}\text{s}$ , the measured emissivity is lower than the expected emissivity for a large range of ionization timescales. Over this range, the O abundance required to be consistent with the model predictions varies from 0.5 to  $5.0 \times$  solar. The O and Ne data are most consistent with each other for a temperature of  $\log(T) = 6.6$  and an ionization timescale of  $4.0 \times 10^{11} \text{ cm}^{-3}\text{s}$ . At these values the Ne abundance is  $\sim$  twice solar and the O abundance is  $\sim$  solar.

#### 4. Discussion

The morphology of the X-ray emission revealed by *Chandra* is more consistent with a SNR shock interacting with an inhomogeneous medium than with a discrete fragment of ejecta. The *Chandra* spectra indicate that Ne is enhanced above solar values, but at a rather modest level, and O is consistent with the solar value. We therefore conclude the *Chandra* observations of the Vela Bullet D region are more consistent with a shock breakout hypothesis than with a bullet of ejecta hypothesis, although the *Chandra* data cannot rule out the bullet idea.

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